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Title: Subband coding for large-scale scientific simulation data using JPEG 2000

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Subband Coding for Large-Scale Scientific Simulation Data Using JPEG 2000

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Scientific Simulation Data

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- Distinct and rather complicated niche in data management and visualization
  - Floating point, analyzed/visualized at 32 bits/sample, fills its numerical range continuously
  - (Often) 2-3 space dimensions + time, with some smoothness
  - Often multicomponent data (e.g., multiple physical fields)
  - May be uniformly gridded, nonuniform but structured, or completely unstructured; stationary or time-varying
- The common feature is size: big and getting bigger

Example:
Global ocean circulation model

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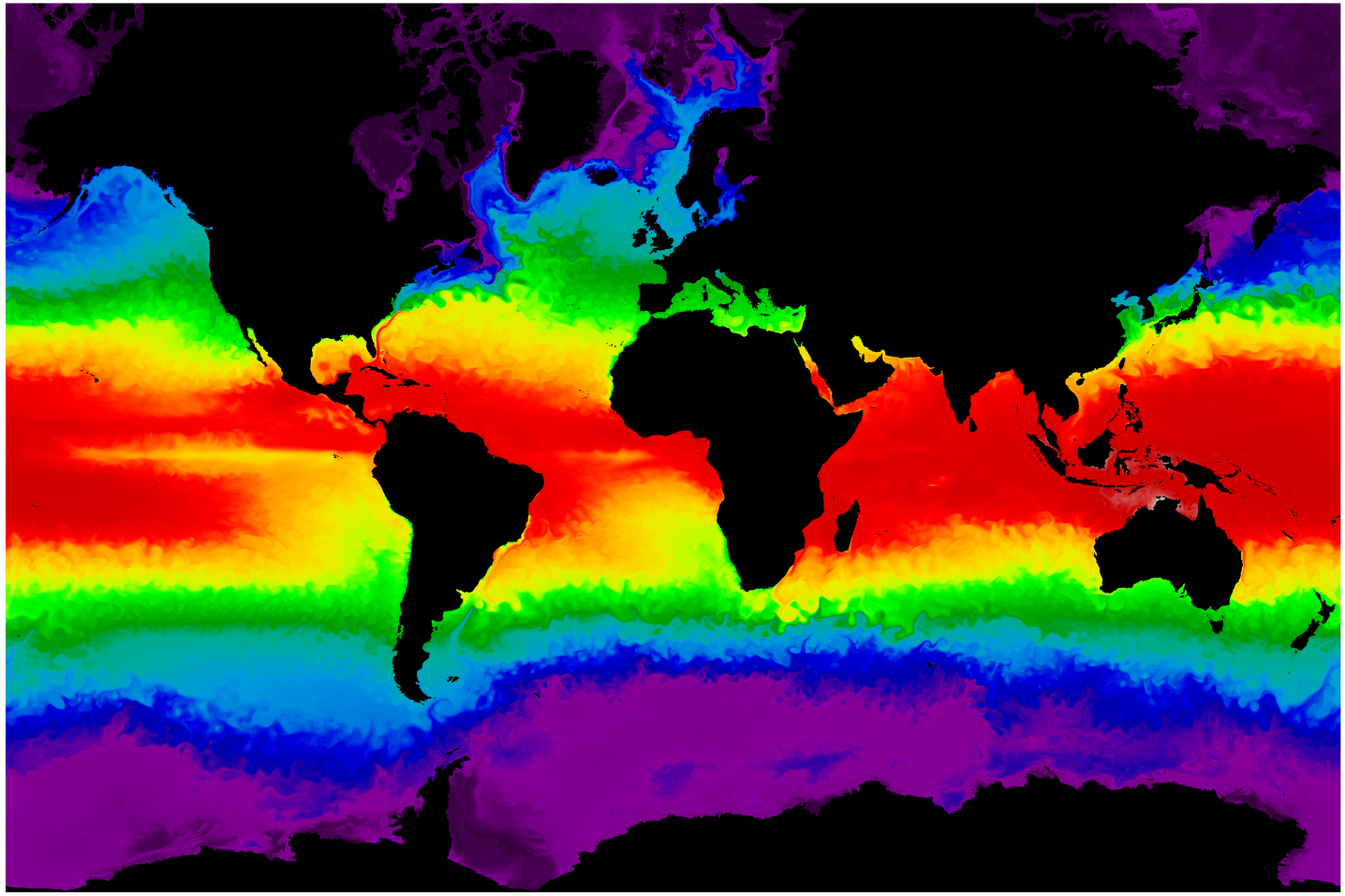
- Parallel Ocean Program (POP) model, run @ ORNL
  - 3600 x 2400 x 42 grid (1/10 degree), 11 km nominal resolution
  - Temp., salinity, x-vel., y-vel. at 32 bits/sample = 5.4 GB/timestep



A sampling of petascale supercomputers (10^{15} ops/sec.)

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- IBM Roadrunner (2008) @ Los Alamos
  - 122,400 cores: hybrid Opteron & PowerXCell architecture; 106 TB memory
  - 1.04 petaflops/s (PF) on Linpack benchmark; power consumption: 2.4 MW
- Cray Jaguar (2008) @ Oak Ridge
  - 224,256 Opteron cores; 300 TB memory; 1.76 PF (Linpack); 7.0 MW
- NUDT Tianhe-1A (2010) @ Tianjin, China
  - 186,368 Xeon & NVIDIA cores; 229 TB; 2.57 PF (Linpack); 4.0 MW
- Fujitsu K Computer (2011) @ Kobe, Japan
  - 705,024 SPARC64 cores; 1410 TB memory; 10.51 PF (Linpack); 12.7 MW
- Unfortunately, petascale computing is still inadequate for resolving some important phenomena:
  - natural length scales (~1 km) of critical features in global ocean and atmospheric models

Petascale inadequate for:

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- inherent uncertainties in turbulent CFD
  - turbulence-chemistry interactions in combustion modeling
  - 85% of world's power supply is generated by burning fossil fuels
- bridging atomistic-molecular-mesoscale-macroscopic scales in materials science and biological systems
- 3-D neutron transport in nuclear reactor cores
- plasma and materials problems in fusion energy production

- Thus, the US Dept. of Energy (DOE) is committed to developing *exascale* computing (10^{18} ops/sec.)
- Sobering expectations of exascale computing:
  - Transistors still getting smaller per Moore's law, but energy efficiency not improving enough for clock freq's to keep increasing
  - Clock stagnation at 2-3 GHz forcing massive parallelism
    - 1 exaflop / 1 GHz = 10^9 cores
  - Memory budget of 100 PB is just 100 MB/core
  - DOE decided a power budget of *just 20 MW* is all they can afford for exascale computing!

Anticipated realities of exascale

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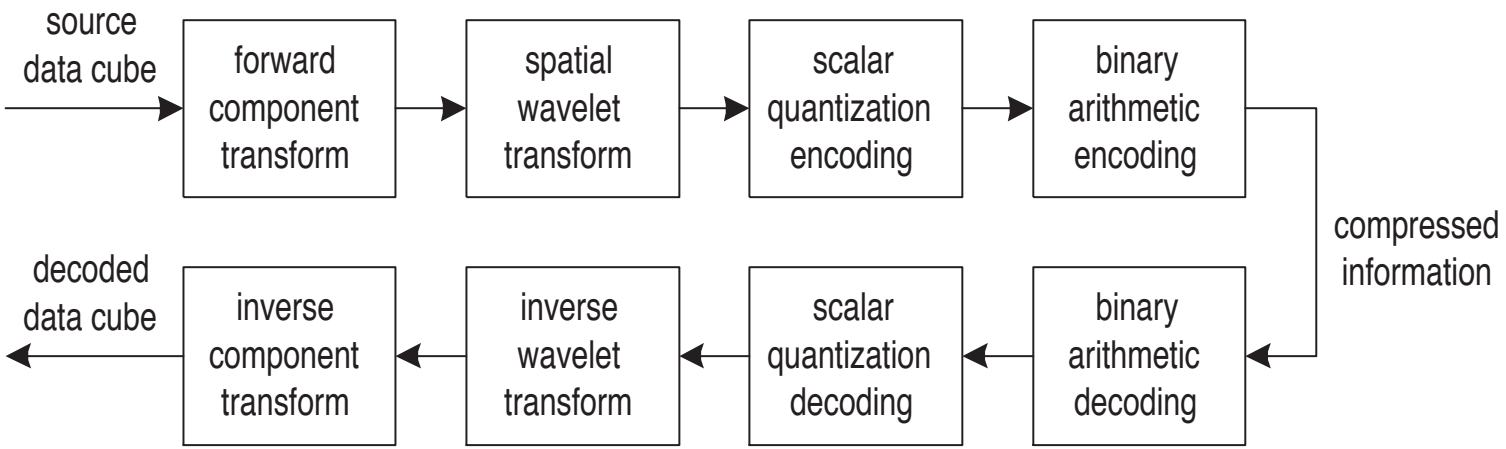
- *Data movement* is single biggest energy cost
  - Energy to fetch a value from (non-cache) memory will exceed energy of a floating point operation
- Current thinking calls for around 1 exabyte of disk storage (1000 PB, or just 10x core memory)
- I/O bandwidth to storage estimated at ≤ 60 TB/s
  - 100 PB memory / 60 TB/s ≥ 28 minutes to write to disk
- We *cannot save* more than a tiny fraction of the data
  - Much analysis and visualization will have to be done *in situ* (while data is still in the machine)
- **Conclusion**: Can't afford *not* to use the most bandwidth-efficient communications coding available for exascale data
  - Computational cost of source coding is *not* the issue: can do a *lot* more flops in exchange for a significant reduction in data

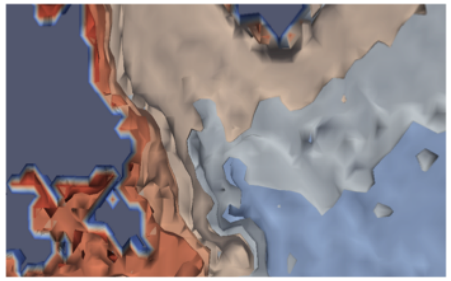
Enter JPEG 2000

- Family of international standards for source coding (compression) of digital imagery (ISO/IEC 15444-x)
  - Supports huge array dimensions, high bit depths, 3-D
  - Highly scalable w.r.t. spatial resolution & reconstructed sample precision, random access to regions-of-interest
  - Standardized HTTP client-server protocol for interactive browsing and retrieval (JPEG 2000 Part 9---"JPIP")
  - "Subband coding scheme": discrete wavelet transforms, embedded binary arithmetic bit-plane coding



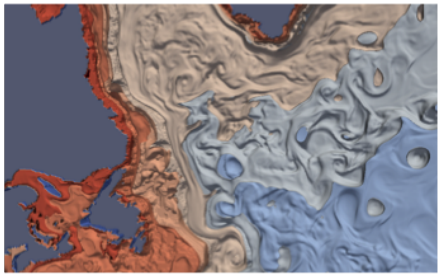
Software Environment

- Currently using “Kakadu” JPEG 2000 software with our own ParaView JPEG 2000 reader + prototype Paraview adaptive multiresolution (AMR) interface:

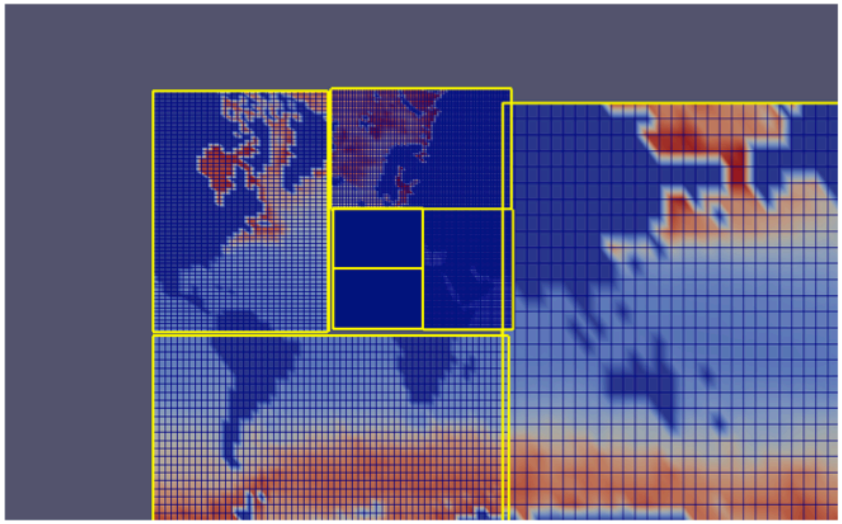


Low-resolution ROI

Streaming interactive update



High-res refinement



Qualitative performance with isocontouring on POP salinity data

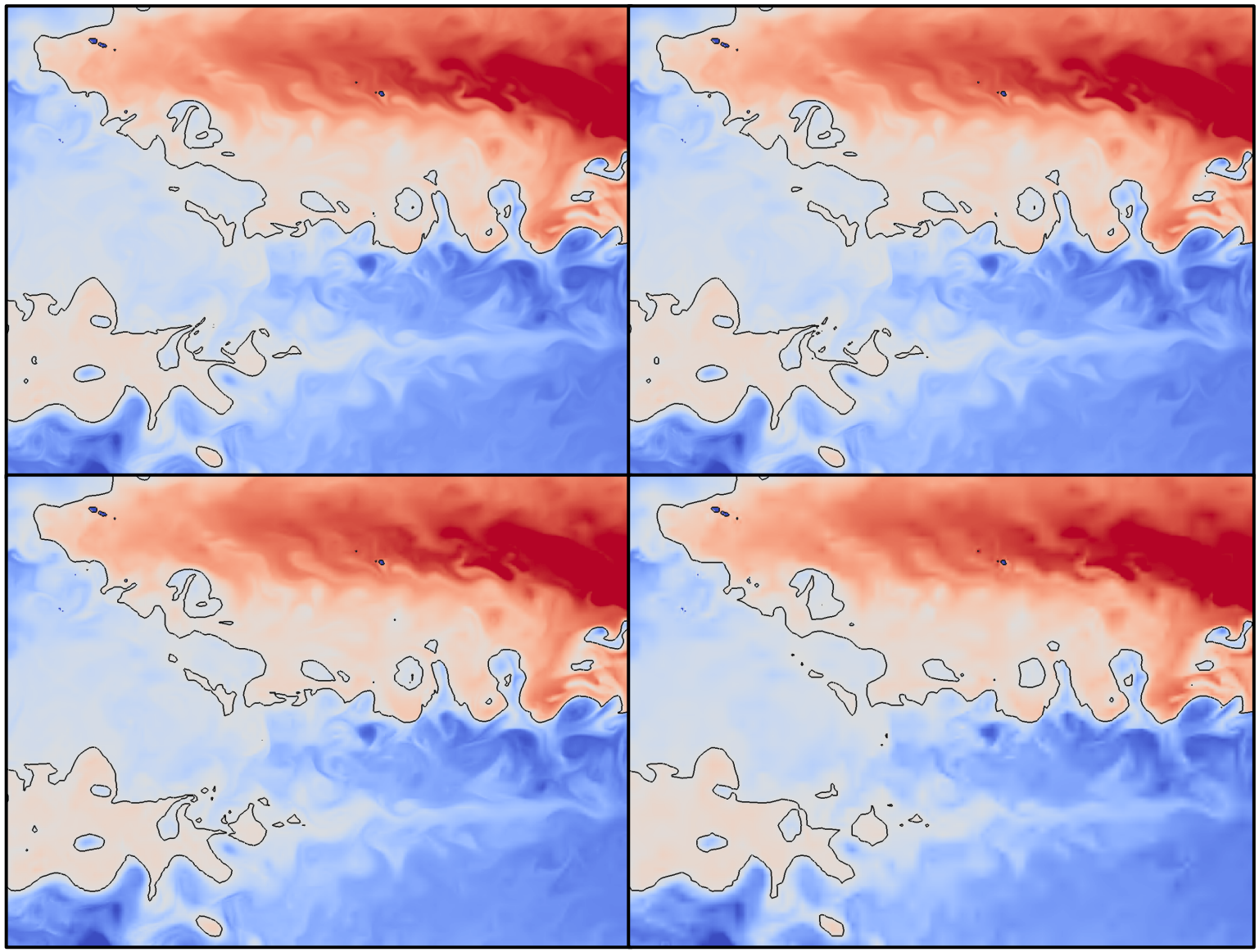
475x358 detail reconstructed at:

(T-L) 8.0 bpp, max.err = 1.5×10^{-9}

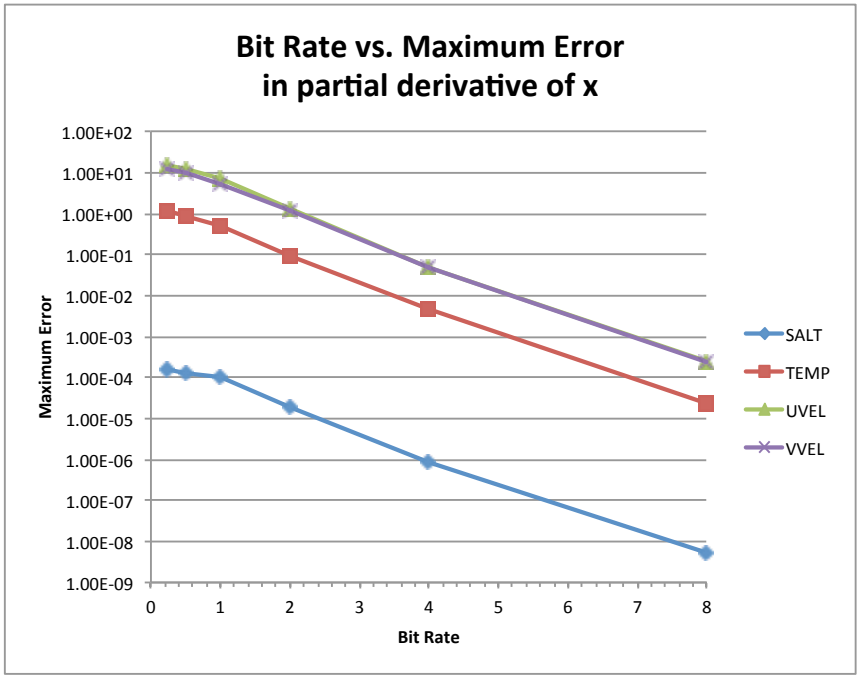
(T-R) 1.0 bpp, max.err = 2.3×10^{-5}

(B-L) 0.5 bpp, max.err = 8.6×10^{-5}

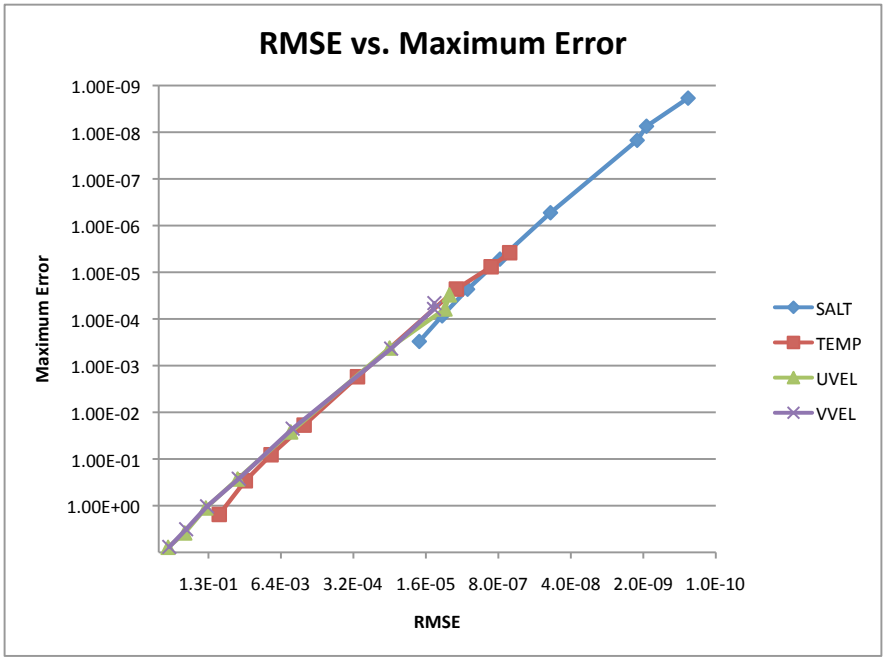
(B-R) 0.25 bpp, max.err = 3.0×10^{-4}



Quantitative rate-distortion performance metrics



Admirably linear behavior, esp. for max. error in numerical derivatives



Empirically, log max. error is proportional to log RMSE, with a data-*independent* constant of proportionality,

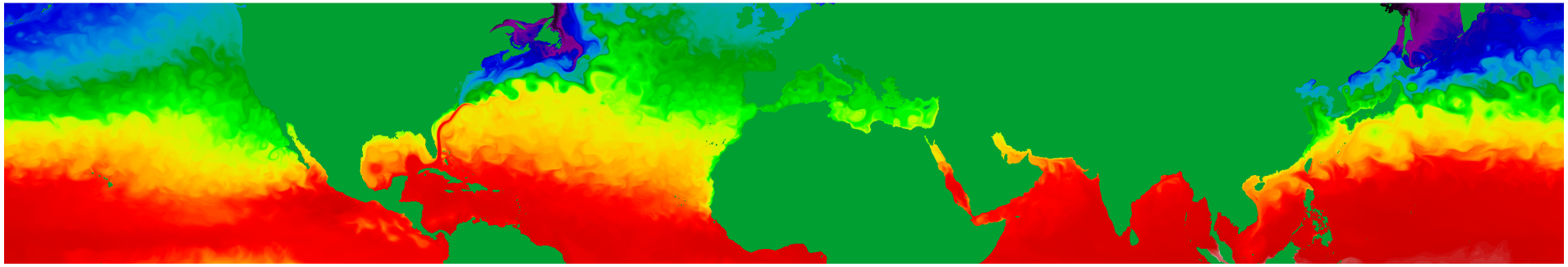
$$\log(\text{max.err}) \approx 10 * \log(\text{RMSE})$$

$$\text{max.err} \approx (\text{RMSE})^{10}$$

(incorrectly stated in paper)

What about masked regions?

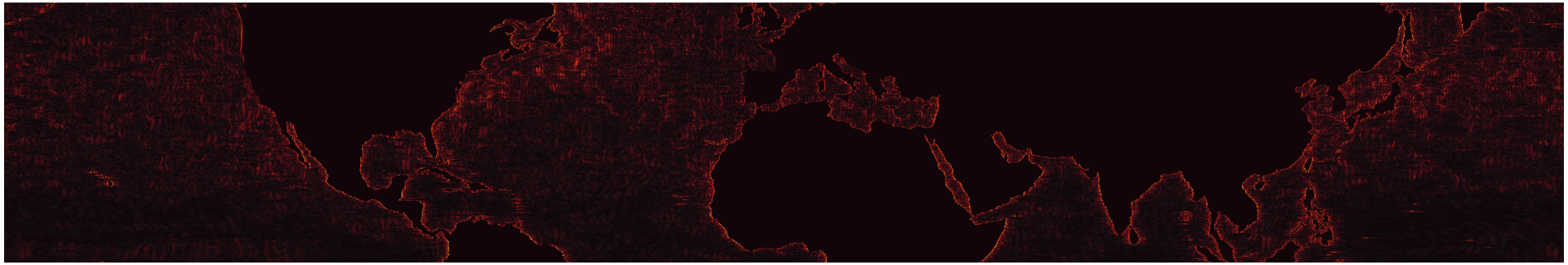
- Fill with a constant value like the global mean of the data.
  - Cheap, hands-off, compressible, but it leaves discontinuities that increase signal entropy and cause artifacts when data is reconstructed at reduced rates.



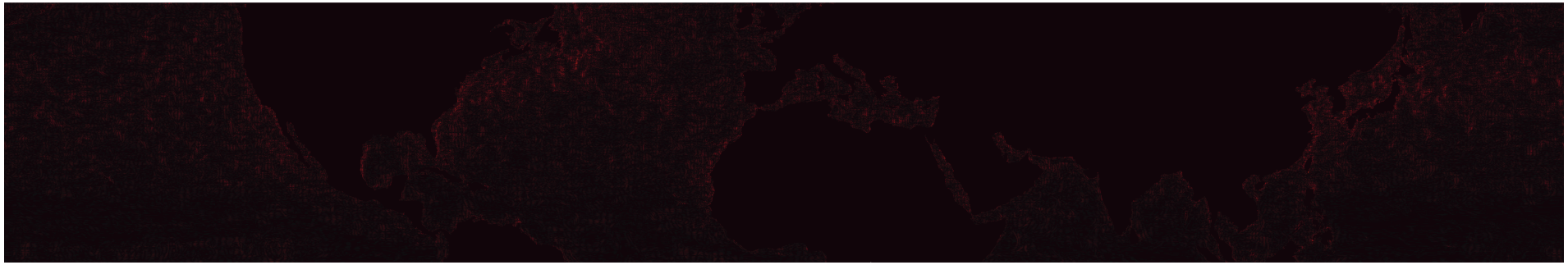
POP surface temperature (25% of the global array), continents filled with global mean of ocean data

Difference Images @ 0.5 bits/sample

- Land masses masked off, error images scaled to have identical “hot” color maps.
- Error image for global mean-filled interpolation. Note concentration of large errors near coastlines:

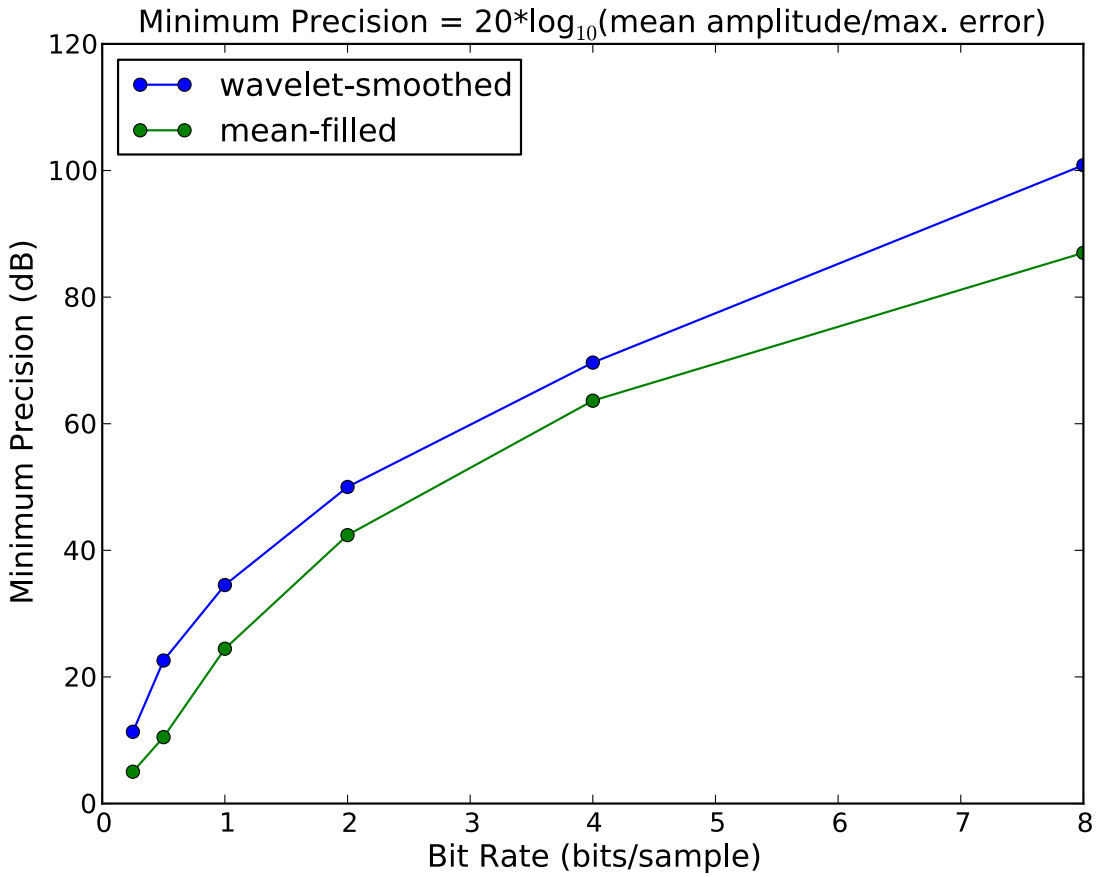


- Error image for wavelet-smoothed interpolation:



Minimum Precision vs. Rate

- Error taken over initialized (meaningful) data only.
  - Difference of 6 to 14 dB: 1 to 2.3 bits diff. in max error.



Conclusions

- Next steps:
  - Enable floating point I/O, entropy estimation for JPEG 2000
  - Extend to 3-D using JPEG 2000 Part 10
  - Interactive client-server semantics between Paraview clients and JPIP servers
  - 2-D and 3-D wavelet-smoothed interpolation of masked regions using matrix-free conjugate-gradient solver
  - In-situ JPEG 2000 encoding for exascale simulations

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  - program manager: Dr. Lucy Nowell